Massive and Red Objects predicted by a semianalytical model of galaxy formation

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ABSTRACT

We study whether hierarchical galaxy formation in a concordance ΛCDM universe can produce enough massive and red galaxies compared to the observations. We implement a semi-analytical model in which the central black holes gain their mass during major mergers of galaxies and the energy feedback from active galaxy nuclei (AGN) suppresses the gas cooling in their host halos. The energy feedback from AGN acts effectively only in massive galaxies when supermassive black holes have been formed in the central bulges. Compared with previous models without black hole formation, our model predicts more massive and luminous galaxies at high redshift, agreeing with the observations of K20 up to $z \sim 3$. Also the predicted stellar mass density from massive galaxies agrees with the observations of GDDS. Because of the energy feedback from AGN, the formation of new stars is stopped in massive galaxies with the termination of gas cooling and these galaxies soon become red with color $R-K>5$ (Vega magnitude) , comparable to the Extremely Red Objects (EROs) observed at redshift $z \sim$1-2. Still the predicted number density of very EROs is lower than observed at $z \sim 2$, and it may be related to inadequate descriptions of dust extinction, star formation history and AGN feedback in those luminous galaxies.

Subject headings: galaxies: formation—galaxies: evolution—galaxies: luminosity function,mass function

1. Introduction

There are many recent observations of high-redshift galaxies that probe the star formation history of the Universe. The finding of many massive galaxies, especially massive

Extreme Red Objects (EROs), at high redshift is particularly interesting. These observations show that some EROs are passive ellipticals, and were already in place at redshift z$\sim$ 2. It is usually argued that in a Cold Dark Matter (CDM) universe, structures form via a hierarchical formation process in which small galaxies form first at early times, and massive galaxies form later through the continuous mergers of the smaller systems. With representative semi-analytical models (SAMs; Kauffmann et al. 1999, Somerville & Primack 1999, Cole et al. 2000), it was found that in the concordance ΛCDM universe, it is difficult to produce enough massive and red galaxies that look like those observed(e.g. Cimatti et al. 2002a, Glazebrook et al. 2004). On the other hand, the existence of the observed massive galaxies at high redshift is not necessarily in conflict with the concordance ΛCDM model, because the conversion of just ten percent of baryons in dark matter halos of mass $M > 10^{13} M_{\odot}$ to stars is sufficient to produce the number of observed massive galaxies (Somerville 2004a).

Many authors have studied the formation of these massive, red objects using SAMs or Smoothed Particle Hydrodynamics (SPH) simulations. It was shown that the SAMs (Kauffmann et al. 1999, Somerville & Primack 1999, Cole et al. 2000) cannot produce enough massive/red objects at redshift $z > 1$ (e.g. Firth et al 2002, Somerville et al. 2004b, Daddi et al. 2005). The SPH simulations (e.g. Nagamine et al. 2004, 2005) have succeeded in producing massive and red galaxies at high redshift, but at the cost of introducing more uncertainties. First, it is unknown if these SPH simulations can produce the local galaxy luminosity function. It seems that these simulations produce too many bright galaxies at $z = 0$ (Nagamine et al. 2004). Secondly, Nagamine et al. (2005) used a high dust extinction for the entire galaxy population, but the observations show that some EROs are passive ellipticals with little dust extinction (Cimatti et al. 2002b).

The main reason that the SAMs fail to produce enough massive and luminous galaxies at high redshift is that the gas cooling and star formation in early massive halos is over-suppressed. In previous SAMs, the gas cooling in massive halos is switched off in order not to produce more luminous central galaxies than observed at redshift $z = 0$. The suppression of gas cooling is also motivated by the X-ray observations that massive cooling flows are not observed in groups and clusters (e.g. Peterson et al. 2003). But as the consequence, the gas cooling may be over-suppressed at high redshift if a simplified prescription is used for the cooling cutoff. For example, in the Munich group model and also in Kang et al. (2005), the gas cooling is shut off by hand in halos with the virial velocity greater than $350km/s$. Since the halo mass is much lower at high redshift than at the present for a given virial velocity, the gas cooling is suppressed in this model for halos with the virial mass greater than $2.5{\times}10^{12} M_{\odot}$ at z = 3. This artificial cooling switch-off seems to be the main reason that these models do not produce as many massive galaxies as observed.

In this paper, we implement a new model in which the energy from AGN is used to suppress the cooling of hot gas in halos. Following Kauffmann & Haehnelt (2000) we use a simple model wherein black holes gain most of their mass during major mergers. Our implementation of the feedback from AGN is very similar to that used recently by Croton et al. (2006) and Bower et al. (2005), and resembles a combination of their models. In our model, the total energy from the AGN is proportional to the Eddington luminosity of the central black hole and the efficiency of reheating the gas is proportional to a power of the virial velocity of the galaxy. Then the energy compensates for the radiative energy of the cooling gas, and the actual cooling rate is determined by the ratio between the two energies. The cooling is totally suppressed if the energy from AGN is larger than the energy radiated by the cooling gas. Compared with the previous model used by Kang et al. (2005) with an artificial cut-off of the gas cooling in the halos with the virial velocity larger than $350km/s$, the gas cooling and AGN feedback in the new model are treated in a more self-consistent way. The $M_{\rm bh}$-σ relation of black hole mass $M_{\rm bh}$ and the bulge velocity dispersion σ implies that massive black holes are present only in massive spheroids. In our present model, the energy feedback from AGN indeed is efficient in galaxies with a massive spheroid. We also require that the star formation rate in quiescent disks is reduced at high redshift as motivated by the observed evolution of cosmological cold gas content with redshift (Keres et al. 2005); thus the gas-rich mergers result in earlier formation of supermassive black holes in massive central bulges. Once the energy feedback is enough to suppress the gas cooling, the termination of new star formation will soon make the galaxies red. We will compare the model prediction of the number density of luminous galaxies with the K20 survey, and find that good agreement holds up to z$\sim$3, beyond which there is little observational data. Compared with previous SAMs, our present model can also produce some very red ($R-K > 5$, magnitudes are given in the Vega system unless otherwise stated) passive ellipticals which are observed by the Great Observatories Origins Deep Survey (GOODS) at z$\sim 1-2$.

We arrange our paper as follows. In section 2, we briefly introduce our new model with AGN feedback and compare our model predictions with the local galaxy population. In section 3, we give the model predictions and compare them with the observations at high redshift. Finally, we discuss our results and conclude our work in section 4.

2. Model

The SAM that we use here was described in detail by Kang et al. (2005) who studied the local galaxy population. The merger tree is constructed based on a high-resolution N-body simulation (Jing & Suto 2002) of 512^3 particles in a box of $100h^{-1}$Mpc. The cosmological

parameters adopted there are $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, $\sigma_8 = 0.9$. Here we still use this simulation, but the SAM model is modified in two ways.

1. We adopt a star formation efficiency $\alpha \sim (1+z)^{-1}$ in a quiescent disk that was shown to give a better match with the evolution of cosmological cold gas content with redshift (Kauffmann & Haehnelt 2000, Péroux et al. 2003, Keres et al. 2005). In the recent model of Durham group (Baugh et al. 2005, Bower et al. 2005), they adopt a constant star formation timescale for the disk. The star formation timescale used in our model is the dynamical time of the disk which scales with redshift as $(1+z)^{-1.5}$. So the star formation rate ($\dot{M}_* = \alpha M_{cold}/t_{dyn}$) of our model differs from that of the Durham model only slightly. Note that the relatively lower star formation rate in quiescent disks leaves more cold gas which helps to produce massive black holes during galaxy mergers at high redshift.

2. We include a model for the growth of black holes and for the energy feedback from AGN to suppress the gas cooling. As the $M_{\rm bh}$-σ relation indicates that the central black holes grow with the growth of the spheroid components, it is plausible that the black holes get their mass through major mergers. But it is far from clear about the exact way that the black holes accrete the surrounding material. Here following Kauffmann & Haehnelt (2000), we use a simple parameterised form to describe the cold gas accreted by the black hole during a major merger,

$$\Delta M_{bh} = F_{acc} \frac{M_{cold}}{1 + (280km/s/V_{vir})^2} \tag{1}$$

where M_{cold} is the total cold gas in merging galaxies, and V_{vir} is the virial velocity of the post-merger host halo. We normalize the parameter F_{acc} by best matching the observed $M_{bulge} - M_{bh}$ relation at z=0 (Häring & Rix 2004). During the gas accretion by black holes, part of the gravitational energy will be converted into radiations which in turn will heat the surrounding cold gas. But it is again unclear in a quantitative way about how much the radiation is produced and how efficiently the cold gas is re-heated. Croton et al. (2006) use a simple phenomenological model to describe the accretion rate which depends on the hot gas fraction and circular velocity of the halo, but the efficiency of heating the gas by AGN are the same in all halos of different mass. Sijacki & Springel (2006) have shown that heating efficiency from a AGN bubble is lower in low mass halos. Here we simply assume that the energy from the central AGN is proportional to the Eddington luminosity L_{edn} and the heating efficiency is proportional to a power of the virial velocity of the host halo. Thus the heating rate ejected into the gas is taken as,

$$L_{reheat} = F_0 (V_{vir}/V_\star)^n L_{edn} \, . \tag{2}$$

If we denote the cooling rate in a halo of gas temperature T by $\dot{M}_{0,cool}$ in the case of no AGN

feedback, then the cooling rate $\dot{M}_{cool}$ in the presence of AGN feedback is:

$$\frac{\dot{M}_{cool}}{\dot{M}_{0,cool}} = 1 - \frac{L_{reheat}}{\frac{3}{4}\dot{M}_{0,cool}V_{vir}^2}. \tag{3}$$

If the heating rate from AGN $L_{reheat}/\frac{3}{4}V_{vir}^2$ is larger than the radiative cooling rate $\dot{M}_{0,cool}$, the gas cooling is totally suppressed. We normalize the parameters F_0, $V_\star$ to get a good match to the galaxy luminosity function at z=0. In our model we obtain $F_0 = 2 \times 10^{-5}$ and $V_\star = 200 km/s$ and $n = 4$.

In Fig. 1 we plot the relation between the bulge mass and the black hole mass. The data points show for the model galaxies and the solid line the best fit to the observations by Häring & Rix (2004). Here F_{acc} is taken to be 0.01. It is seen that a simple model of black hole growth with a free parameter can reproduce the observed $M_{bulge} - M_{bh}$ relation. After the black hole mass is normalized, we then tune the parameters in equation 2 to get good fits to the local galaxy luminosity functions. In Fig. 2 we show the luminosity function at B_j and K bands. The upper panel shows a comparison with the 2dFGRS at B_j band. The solid circles show the observational data of 2dFGRS, and the thick solid histogram associated with Poisson errors is our model prediction.

The lower panel shows the comparison at K band where the circles are from Cole et al. (2001) and squares are the observations by Huang et al. (2003). We find that the new model can produce the local galaxy luminosity functions at blue and near-IR bands which are respectively sensitive to the current star formation rate and the total stellar mass in the galaxies. It has been shown (Croton et al. 2006, Bower et al. 2005) that without an effective energy feedback, the predicted luminosity functions at the bright end are too flat with many more luminous galaxies predicted than observed. Note that here our model predictions at high luminosity ends are still slightly higher than observed. This might point to the fact that a more detailed model is needed for AGN heating in massive halos which we will address in future work.

3. Results at high redshift

As discussed in Section 1, the gas cooling in our new model is not suppressed artificially but by heating due to the energy injected from AGN in the galaxy center. So compared to previous SAMs without AGN, the gas cooling and star formation can continues until a massive spheroid forms at the galaxy center. It is expected that this model can produce more massive and luminous galaxies at high redshift. In Fig. 3 we show the predicted rest-frame K band luminosity function at z$\sim$ 1.5. The squares with error bars are the observational

results from K20 (Pozzetti et al. 2003). The solid circles are the predictions by the new model and the triangles show the results predicted by Kang et al. (2005) where they adopted a artificial shut off of gas cooling in galaxies with $V_{vir} > 350km/s$. We also re-plot the results of K band luminosity function at z=0 by the solid line, taken from from lower panel of Fig.2. It is clearly seen from the plot that the new model produces more massive galaxies and the agreement with the observations is very good. Also note that the good agreement holds for faint galaxies as well, whereas it was reported previously that SAM models produce more faint galaxies than observed (Pozzetti et al. 2003).

Another test, firstly proposed by Kauffmann & Charlot (1998), is the evolution of the surface number density of galaxies at a fixed limiting magnitude, which also widely used to constrain the models. There are plenty of data from GOODS that are already publicly available (Giavalisco et al. 2004). In Fig. 4 we show the predicted redshift surface number density of galaxies with K$<$ 20. The square points show the results of K20 and triangles are the data from GOODS. The new model predictions are shown as the solid line, and the dashed line shows the prediction by the model of Kang et al. (2005). Here we find that compared with Somerville et al. (2004b) who predicted much fewer luminous galaxies at $z > 1.5$, the agreement between our model and the observations holds much better up to z$\sim$ 3. Here we also show how dust extinction will change the result. The dotted line is the new model with the simple dust extinction model of Calzetti et al. (2000) with $E(B-V) = 0.1$. Clearly dust extinction has no significant effect on the predicted number of galaxies in the observed-frame K band up to z=3.

Though the predicted numbers of luminous galaxies agree with the observations, it would be interesting to check the predicted color distributions. The color is dependent on the star formation history and on the dust extinction. At high redshift the galaxy mergers are very frequent and the dust extinction is significant in these starburst galaxies, but no reliable model of dust extinction is available for such galaxies. Observations show that at z$\sim 1-2$ the EROs have contributions both from passive ellipticals with little dust and from dust-enshrouded starburst galaxies (Cimatti et al. 2002b, Cimatti et al. 2003, Yan & Thompson 2003, Yan et al. 2004, Moustakas et al. 2004). Because there are significant uncertainties in the dust extinction modelling for the starburst galaxies, we think that the predicted number density of passive ellipticals should set a more meaningful constraint on the galaxy formation model. Here we take a simple model of dust extinction. We classify the galaxies with starbursts produced during the major mergers in the past 0.1Gyr as young starburst galaxies and those otherwise as passive galaxies. We then use the Calzetti et al. (2000) reddening law to model the dust extinction effect on the galaxy color. The amount of dust in passive and young starburst galaxies is difficult to assess, and here we simply assume a small reddening $E(B-V) = 0.05$ for the passive galaxies. The dust extent in young

starburst galaxy is expected to be high. Observations of EROs show that some extremely red galaxies have heavy dust extinction with $E(B-V)=0.4$. But the average extinction should be lower. Here we assume a Gaussian distribution of $E(B-V)$ with a mean of 0.1 and a dispersion of 0.05 for the young starburst galaxies. Our main motivation is to see if a simple dust reddening model can produce the main features of the observed color distribution.

In Fig. 5 we show the observed $R-K$ (both in the AB magnitude system, $(R-K)_{AB} \simeq (R-K)_{Vega} - 1.65$) color distribution with a comparison with the data which are from the GOODS Southern field in an area of 160 arcmin^2 (Somerville et al. 2004b). The upper panel shows the GOODS data, which is from Figure 2 of Somerville et al. (2004b). The model galaxies are selected using the magnitude cut and are normalized to the same area of 160 arcmin^2. The total number of galaxies selected in our model is 1595 which is 6% higher than the GOODS data points used here. The lower panel shows the model predictions. In each panel we also show the evolution track of single burst stellar populations with solar metallicity, the Salpeter IMF, and the ages (at $z=0$) of 13.35 and 11.7 Gyrs (i.e. $z_f = 26, 2.6$) based on the model of BC03 (Bruzual & Charlot 2003). From the figure, our model can reproduce the main features of the observed galaxies: 1) many extremely red galaxies ($R-K>4$) at $z>1$; 2) the bimodal color distribution, red passive and young starburst galaxies at $z>1.5$. Still there are some discrepancies. The predicted numbers of blue galaxies are too prominent at z< 1.5 and this might be due to the inadequate treatment of star formation rate, stellar initial mass function, or the dust extinction model. Also the predicted number of extremely red galaxies with $(R-K)_{AB} > 3.35$ at $z \sim 2$ is still lower than observed. In our model there are enough luminous galaxies but insufficient number of very red galaxies, which means that the star formation (at ~ 2) in the current model are still high. There are two possible reasons for this discrepancy. First the star formation is not strong enough in the past in our model, as we do not include any star formation during minor mergers which are also frequent at early times. Second the energy from central AGN is not high enough to suppress the hot gas cooling. Observations have shown that there are already massive black holes ($\sim 10^9 M_\odot$) at $z \sim 6$ (Fan et al. 2001), so the growth of black holes in massive galaxies might be much quicker at early time than in our model in which the fraction of cold gas accreted by black hole is constant with time. We will address this in a forthcoming paper (Kang et al. 2006).

Glazebrook et al. (2004) used the Gemini Deep Deep Survey (GDDS) to obtain the stellar mass distribution from $z \simeq 0.7$ to 2. The evolution of stellar mass density does place important constraints on the formation model of massive spheroids. But due to the uncertainties in fitting the multi-broad band colors of high redshift galaxies including those of the IMF and dust extinction, the constraints are weak. In Fig. 6, we show the stellar

mass density of galaxies with stellar mass above certain limits. The lines show the predicted stellar density in galaxies with stellar mass in the range indicated in the plot. Black lines are for this model and blue lines are from the model of Kang et al. (2005) where they used an artificial cut of gas cooling in the halos with $V_{vir} > 350km/s$. We can still see a good match between the model and the data. Although it seems that the stellar mass density with $M_\star > 10^{10.46} M_\odot$ is higher than the data points, it agrees with the integral of the star formation rate (see figure 4 of Glazebrook et al. 2004). Note that galaxies with $M_\star > 10^{11} M_\odot$ are in the sharply declining tail of the mass function, therefore a small uncertainty in the estimated stellar mass can introduce a very large uncertainty in the number density. The hexagon in the plot shows the stellar mass density of massive galaxies with $M_\star > 10^{11} M_\odot$ recently obtained by van Dokkum et al. (2006) making use of the deep multi-wavelength GOODS, FIRES and MUSYC surveys. It is seen from the black dashed lines that our model prediction is slight lower than the data by a factor of 2. At high redshift the cosmic variance is so large in the observed catalogs (about 60%, Somerville et al. 2004c) that the discrepancy might not be serious.

4. Discussion

Here we have implemented a new semi-analytical model in which the energy from AGN suppresses hot gas cooling in massive halos. The growth of black holes and bulges, and the gas cooling, are determined in a self-consistent way. In our description, the AGN feedback becomes efficient in massive galaxies after a massive black hole is formed in the galaxy center. The AGN feedback model has drawn much recent attentions. The main motivation is that in massive groups and clusters cooling flows are not observed. There should be some physical process to reheat the cooling region, and the energy from AGN has been proposed as an effective source (e.g. Böhringer et al. 2002, Begelmen et al. 2002, Sijacki & Springel 2006). At the same time, the AGN feedback models have also been incorporated into the SAMs recently and it has been shown that AGN feedback can produce a break of the luminosity function at the bright end and produce the color-magnitude relation observed in SDSS (Croton et al. 2006, Bower et al. 2005). Our model of AGN feedback is very similar to theirs in spirit, but the detailed prescription is different. In this paper we use this model to address some issues about the number distribution and color distribution of galaxies at high redshift. We compare the model predictions with the K20 and GOODS surveys. Our conclusions are as follows.

- The predicted number distribution of $K < 20$ galaxies matches well with that of the GOODS and K20 galaxies up to a redshift of z $\sim$ 3;

- The predicted color distribution is similar to that observed in the surveys and many extremely red galaxies ($R - K_{AB} > 4$) are produced, which has not been seen in previous models (Somerville et al. 2004b). At $z > 1.5$ the galaxy population already displays a bimodal color distribution;

- The predicted stellar mass density can marginally agree with the GDDS observation even with the uncertainties in the IMFs;

These results demonstrate that it is not difficult to produce massive and red galaxies at z $\sim$ 1-2 in the concordance CDM universe. The stellar mass in galaxy centers continues to grow until the energy from central AGN is high enough to suppress the gas cooling. In our model the black holes acquire most of their mass during major mergers, so the AGN energy feedback is expected to be effective after the last major merger which led to massive bulge formation at galactic centers. In our model we can produce some of those passive ellipticals at z$\sim 1-2$ with extremely red colors $(R-K)_{AB} > 4$.

Many observations have shown that the star formation rate was higher in massive galaxies at high redshift and these support the "downsizing" formation scenario (Cowie et al. 1996). It is often argued that hierarchical galaxy formation cannot reproduce the downsizing formation process. But recent works (de Lucia et al. 2005, Bower et al. 2005, Scannapieco et al. 2005) have shown that models with AGN feedback in the hierarchical universe can reproduce the downsizing process in which the massive galaxies forms earlier. In this paper, we also find that the predicted luminous and massive galaxies are increased to the degree that is in agreement with the observations, though the predicted number of red galaxies may still be fewer than observed. Once more observations are available on the dust extinction in these galaxies, the number density and evolution of red passive ellipticals will put more stringent constraints on the galaxy formation models. It is also possible that a new ingredient is needed, such as the star formation induced by AGN feedback prior to disruption of the cold gas supply (Silk 2005), in order to make bulge formation more efficient and to account for the chemical evolution of massive early-type galaxies.

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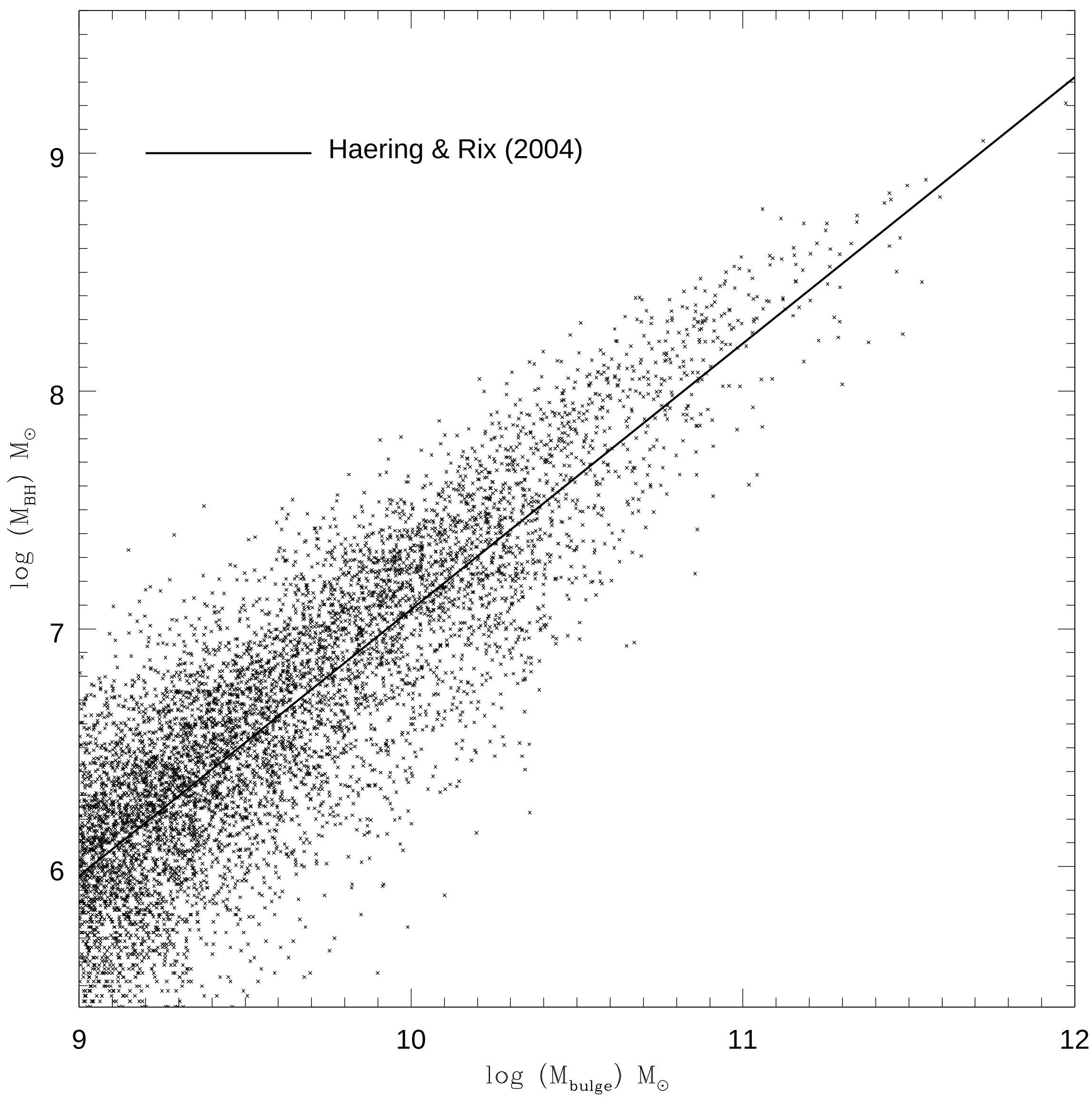

Fig. 1.— The relation between the mass of the bulge and the black hole for local galaxies. The crosses are the model galaxies and the solid line is the best fit to the observations (Häring & Rix 2004).

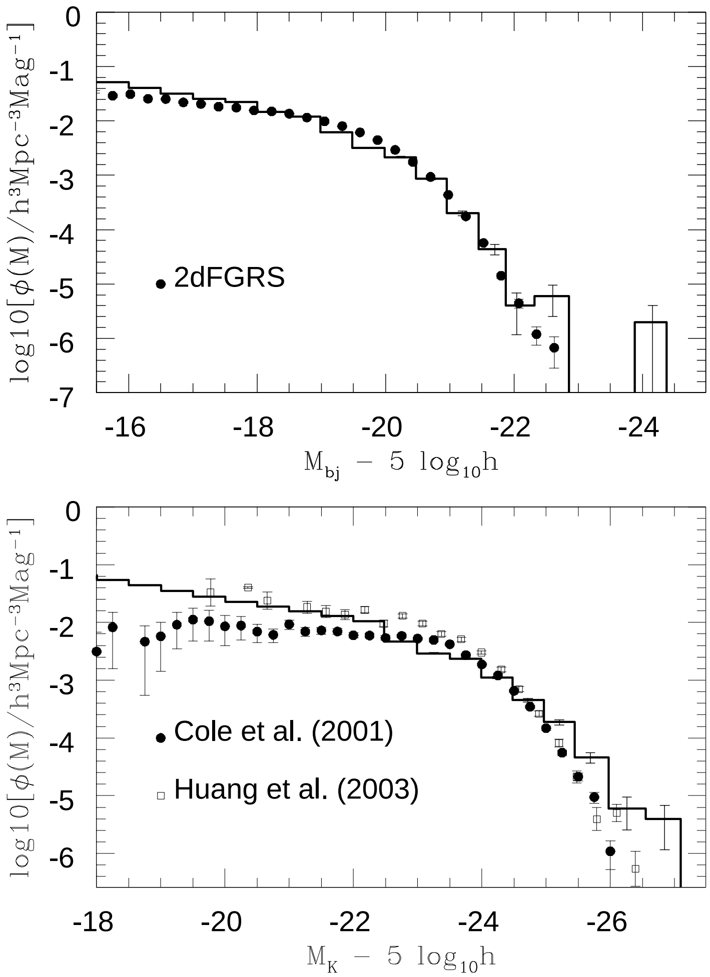

Fig. 2.— The local galaxy luminosity function. Upper panel: the B_j band luminosity function, and the data points are from the 2dFGRS (Norberg et al. 2001). Lower panel: the K band luminosity function, and the data points are from observations of Cole et al. (2001) and Huang et al. (2003). In both panels, the histograms associated with Poisson errors are the model predictions.

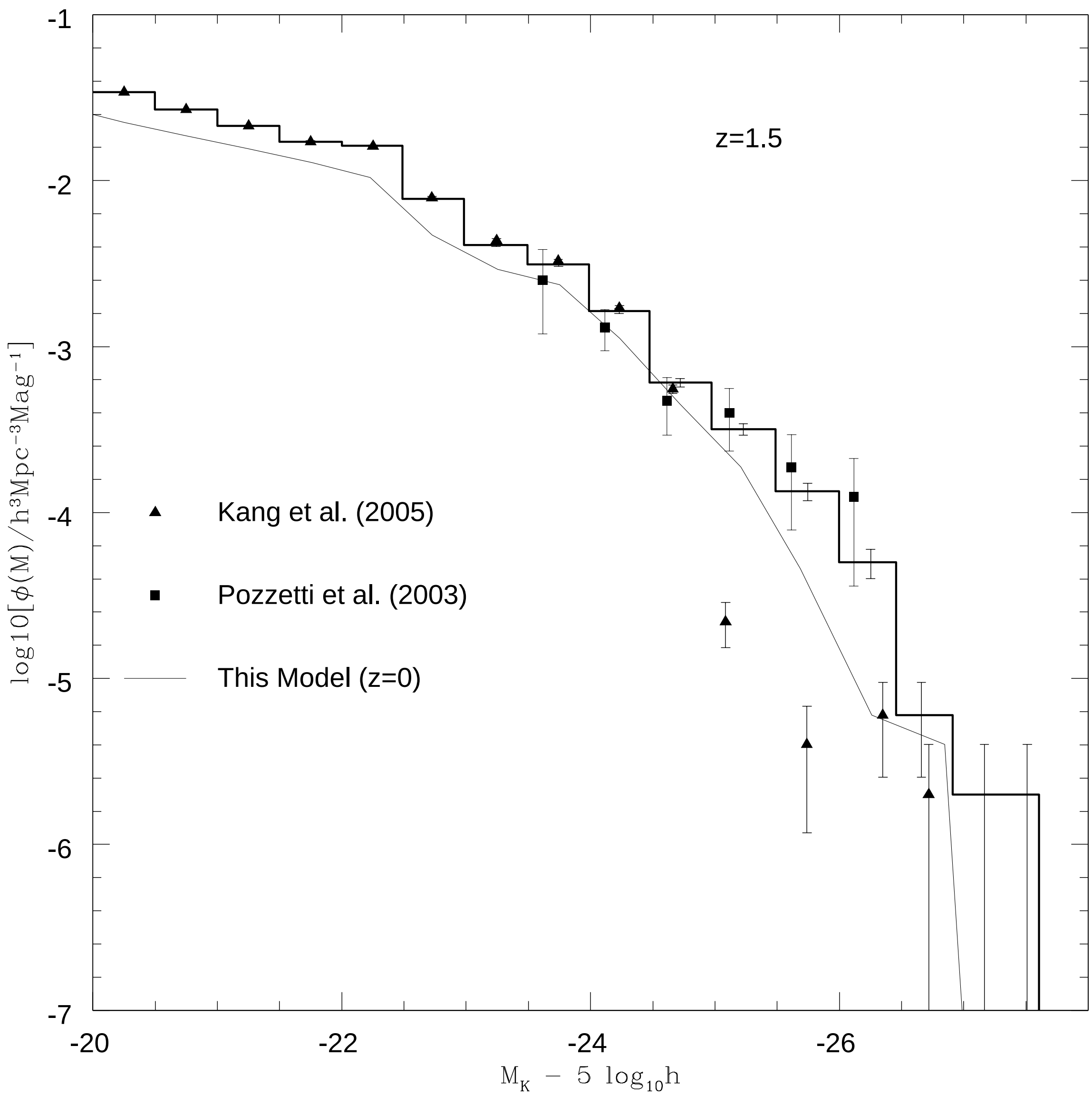

Fig. 3.— The rest-frame K band luminosity function at $z = 1.5$. The data points with errorbars are the observations of K20 (Pozzetti et al. 2003). The histograms are our new model with AGN feedback, and the triangles are the prediction by Kang et al. (2005) where they used an artificial cooling cut for halos with $V_{vir} > 350km/s$. The solid line is the local K band luminosity function from our new model, shown also as the histogram in the lower panel of Fig2.

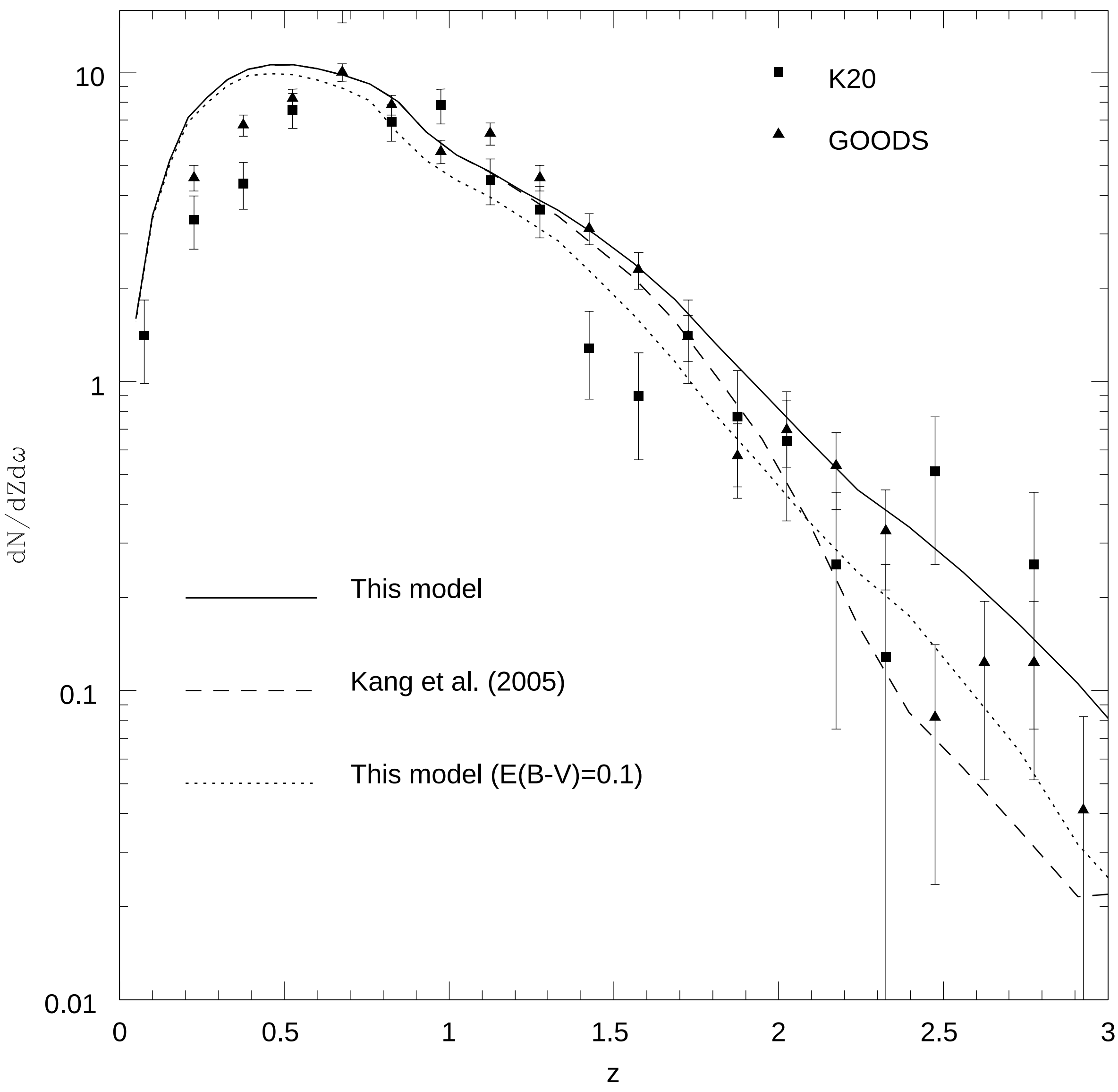

Fig. 4.— The redshift surface density distribution of $K < 20$ galaxies. Data points show the observations, solid and dashed lines are the model results without dust extinctions, and the dotted line is for a simple reddening law of Calzetti et al. (2000) with $E(B-V) = 0.1$.

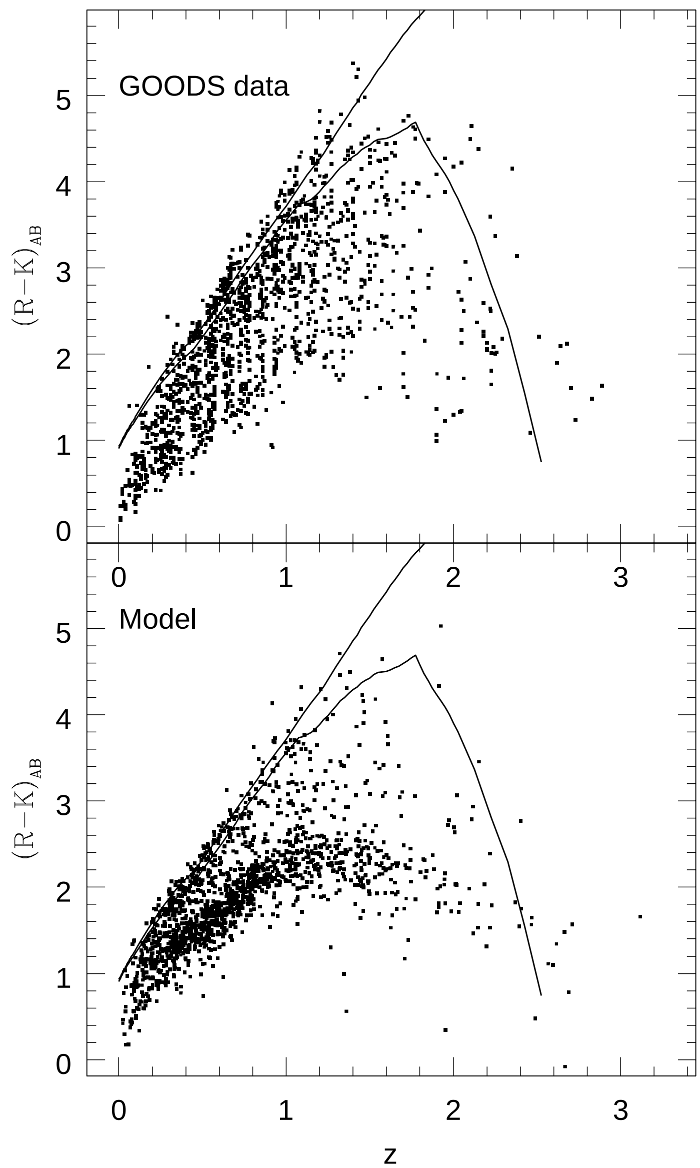

Fig. 5.— $R - K$ color distributions in the observed frame. Upper panel: the GOODS data from Fig.2 of Somerville et al. (2004a). The lower panel: the model galaxies with a simple dust extinction.

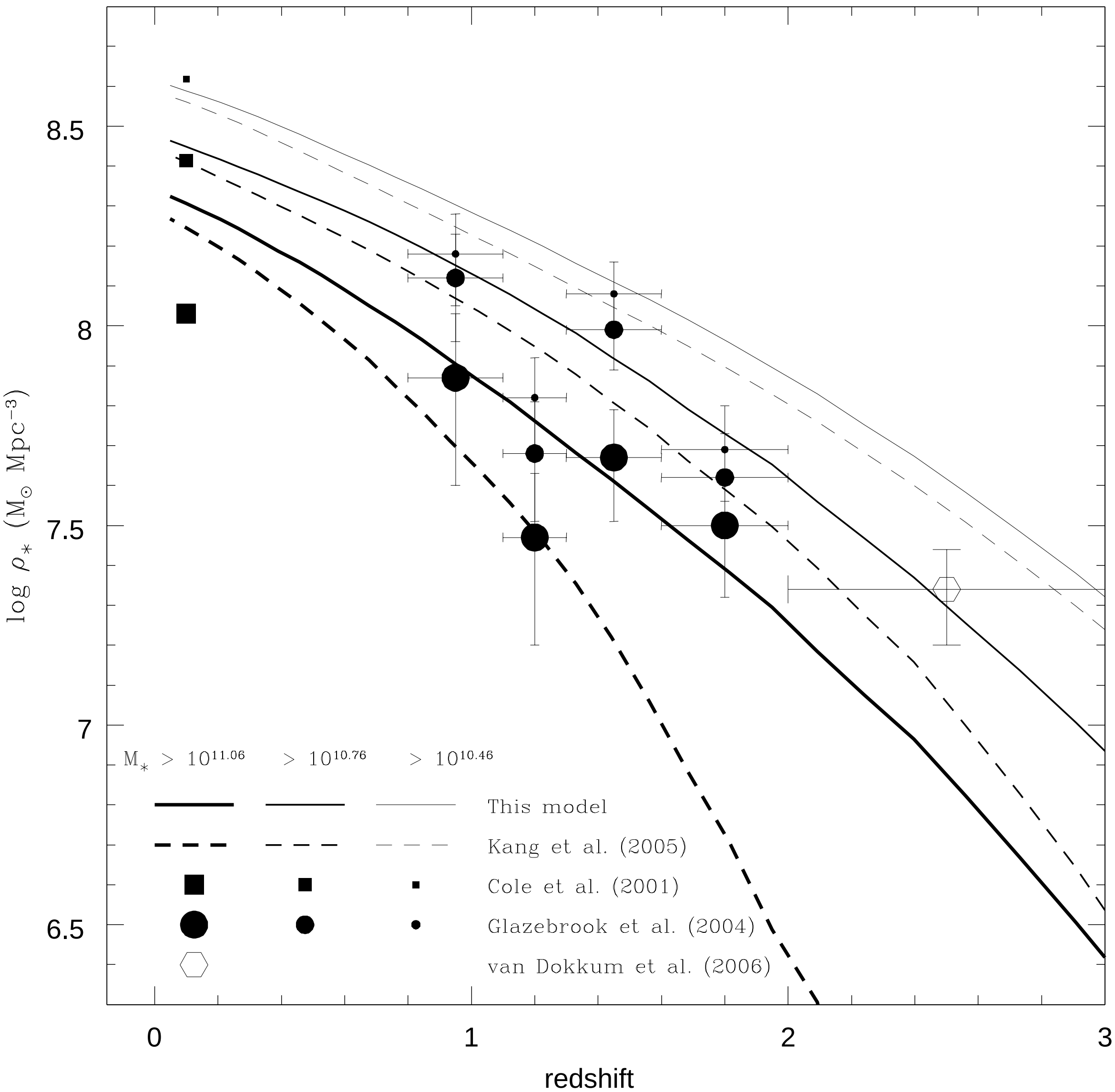

Fig. 6.— The stellar mass density as a function of redshift for galaxies with stellar mass above certain threshold. The mass thresholds are indicated in the plot. The data points are from Glazebrook et al. (2004), but have been transformed to the case of the Salpeter IMF. The lines are the model results, see the text.